ON THE DIFFERENCES IN ELEMENT ABUNDANCES OF ENERGETIC IONS FROM COROTATING EVENTS AND FROM LARGE SOLAR EVENTS

D. V. REAMES, I. G. RICHARDSON,[1] AND L. M. BARBIER
Laboratory for High Energy Astrophysics, Code 661, NASA/Goddard Space Flight Center, Greenbelt, MD 20771

ABSTRACT

We have examined the abundances of energetic ions accelerated from high-speed solar wind streams by shock waves formed at corotating interaction regions (CIRs) where high-speed streams overtake the lower speed solar wind. The observed element abundances appear to represent those of the high-speed solar wind, unmodified by the shock acceleration. These abundances, relative to those in the solar photosphere, are organized by the first ionization potential (FIP) of the ions in a way that is different from the FIP effect commonly used to describe differences between abundances in the solar photosphere and those in the solar corona, solar energetic particles (SEPs), and the low-speed solar wind. In contrast, the FIP effect of the ion abundances in the CIR events is characterized by a smaller amplitude of the difference between high–FIP and low–FIP ions and by elevated abundances of He, C, and S. It is likely that these differences in abundances can be understood in terms of higher temperatures and shorter time scales in the chromospheric fractionation region of coronal holes. Similar processes could also cause the enhanced C/O ratio and the strong suppression of He in the Galactic cosmic-ray sources.

Subject headings: cosmic rays: abundances — Sun: abundances — Sun: corona — Sun: solar wind

1. INTRODUCTION

It has been known for some time (see review by Meyer 1985a, b) that the abundances of elements observed in the solar wind and in solar energetic particle (SEP) events reflect the abundances in the solar corona. This allows the solar wind and SEP abundances to serve as proxies for the coronal abundances and permits us to extend our knowledge of the coronal abundances to elements that are otherwise inaccessible. Abundances of elements in the corona differ from those in the photosphere (Meyer 1985a, b) in that the elements with values of first ionization potential (FIP) above ~10 eV (S, C, O, N, Ne, and He) are suppressed by a factor of about 4 relative to elements with lower FIPs (Ca, Mg, Fe, and Si). More recent observations of both solar wind (Bochsler, Geiss, & Kunz 1986; Schmid, Bochsler, & Geiss 1988; Gloeckler & Geiss 1989) and SEP (Breneman & Stone 1985; McGuire, von Rosenvinge, & McDonald 1986; Cane, Reames, & von Rosenvinge 1991) abundances continue to support the description given by Meyer. The fractionation of the coronal abundances is believed to result from differences in the transport of charged and neutral ions as they move upward along magnetic field lines in the chromosphere near the base of the corona (Vauclair & Meyer 1985; von Steiger & Geiss 1989) where the electron temperature is ~8000 K. Once ions reach the corona or solar wind, they have attained high ionization states typical of temperatures over 10^6 K, so they are no longer distinguished by their FIP.

In recent years, however, there has been increasing evidence that coronal abundances are not uniform. EUV and XUV observations of spectral lines in the corona (Widing & Feldman 1989; Feldman & Widing 1990; Feldman, Widing, & Lund 1990) show large variations in the Ne/Mg ratio, for example, that depend upon the morphology of the magnetic field. Feldman et al. (1990) suggest that the abundance of S can

shift to one appropriate to the low–FIP group if the temperature of the fractionation region rises. Meanwhile, Gloeckler & Geiss (1989) have succeeded in measuring abundances in high-speed solar wind streams that have been slowed by entry into Earth's magnetosheath. They find a decrease in the magnitude of the enhancement of the low–FIP elements in comparison with that in low-speed streams or SEP events.

Increases in MeV ion intensities that appeared to corotate with the Sun were first reported by Bryant et al. (1965). These ions are now known to be accelerated from the solar wind by a pair of shock waves bounding corotating interaction regions (CIRs) (see Pesses et al. 1979) where high-speed solar wind streams, emerging from coronal holes, overtake low-speed streams (Smith & Wolfe 1979). Generally, the shock pairs form outside 1 AU. A "forward" shock propagates outward through the low-speed solar wind stream and a "reverse" shock inward through the high-speed stream. Energetic ions are observed primarily in the high-speed streams, flowing predominantly sunward along the field lines (in the plasma rest frame) from the direction of the reverse shock. Element abundances in these energetic ions have a reasonably well-defined and unusual character (McGuire et al. 1978; Gloeckler et al. 1979; Scholer, Hovestadt, & Klecker 1979). In particular, the C/O and He/O ratios are substantially higher than those in the standard photospheric or coronal abundance schemes. In fact, the value of C/O ≈ 1.0 in CIR events more closely resembles the value found in Galactic cosmic rays than the value of C/O ≈ 0.5 found in the photosphere or in the SEPs. No satisfactory explanation for the CIR abundances has been advanced, and their FIP–dependence has not been understood previously.

The abundances commonly described as SEP abundances actually come from measurements in large "proton" events that are distinct from impulsive solar flares (Reames 1990a; Reames, Cane, & von Rosenvinge 1990). Particles in these large proton-rich events are believed to be accelerated from

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[1] Also Astronomy Department, University of Maryland.

L43

ambient material in the corona or solar wind by shock waves driven by large coronal mass ejections (Cane, Reames, & von Rosenvinge 1988; Kahler, Reames, & Sheeley 1990; Reames 1990b). SEP abundances do exhibit event-to-event variations that depend upon the charge-to-mass ratio, Q/A, of the ions (Breneman & Stone 1985). These variations presumably depend upon the properties of the individual shocks and thus tend to cancel when many events are averaged (see Cane et al. 1991).

The current understanding of the origin of the CIR and SEP abundances, therefore, leaves us with an unanswered question. What mechanism can cause these differences in the FIP–dependent fractionation in different regions of the chromosphere?

2. OBSERVATIONS

To compare CIR and SEP abundances, we use > 2.0 MeV amu^{-1} energetic particle measurements that were made by the Very Low-Energy Telescope (von Rosenvinge et al. 1978) on the *ISEE 3/ICE* spacecraft. From 1978 August through 1982 September the spacecraft remained in orbit about the sunward L1 libration point, 240 Earth radii upstream of Earth. Following a series of excursions into the geomagnetic tail region in 1983, the spacecraft began to move ahead of Earth in solar orbit. The average abundances from 36 large SEP events measured by this experiment were published by Cane, et al. (1991). Abundances in corotating events were determined in a sample of 25 corotating streams that occurred between 1982 January 1 and 1987 January 1.

The CIR–related events were identified by the presence of high-speed solar wind streams and by the observation of sunward-flowing energetic particles in the streams on multiple solar rotations or on multiple spatially separated spacecraft. Time profiles of particle intensities and plasma parameters are shown for a corotating event in Figure 1. The time periods of the two observations of a recurrent high-speed stream, separated by one 27 day solar rotation period, can be seen in the figure. Increases in the plasma density and magnetic field that precede the high-speed stream arise from the stream interaction and define the CIR itself. Particle abundances are accumulated only during the time periods indicated by the horizontal bars shown in each panel to ensure measurement during the high-speed stream. However, it is clear that the C and O intensities are statistically equal during most of the time period shown. The C, O and He abundances are characteristic of CIR–associated events. Further details of this study will be published elsewhere (Richardson et al. 1991).

Average element abundances from the SEP and CIR populations are divided by the corresponding photospheric (" solar system ") abundances of Anders & Grevesse (1989) and plotted as a function of FIP in Figure 2. No corrections for Q/A have been applied to either population, and the lack of need for such corrections can be seen by comparing the abundances of Mg, Si, and Fe. These elements are closely spaced in FIP but differ greatly in Q/A, yet they show similar enhancements in Figure 2. Thus, in the terminology of Meyer (1985a), these SEP and CIR abundances are already " mass-unbiased."

The element abundances in the individual populations are given in Table 1. Both the SEP and CIR abundances are in excellent agreement with previous observations mentioned above. The advantage of the new *ISEE 3* measurements is their improved statistical accuracy and the freedom from possible instrument bias that accrues because both populations were measured with the same instrument.
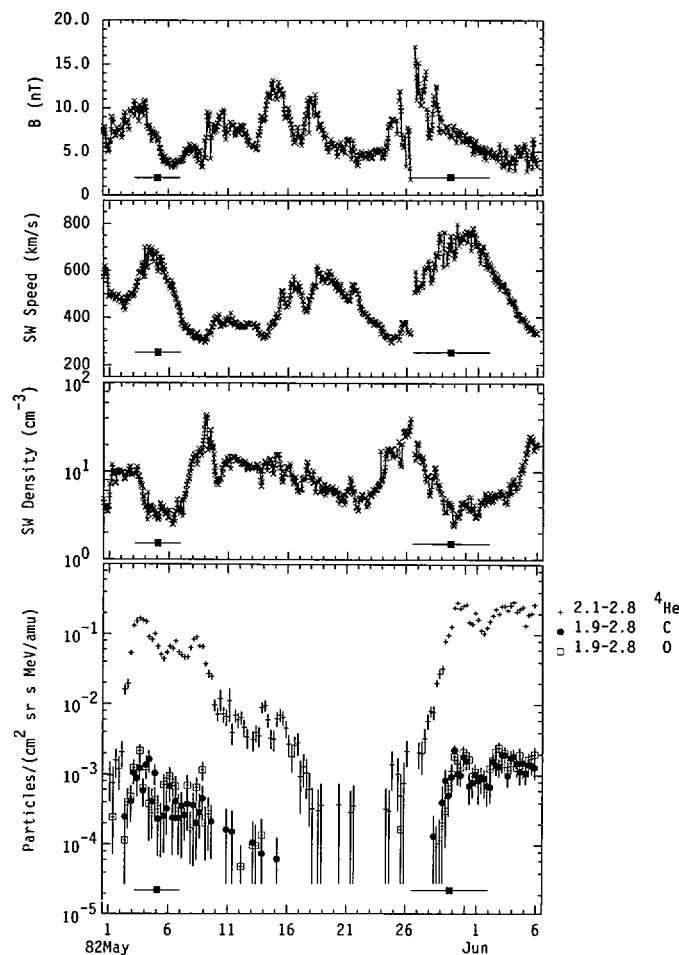

Fig. 1.—Particle intensities and plasma parameters showing strong particle increases associated with a recurring high-speed solar wind stream. The two increases are separated by the 27 day solar rotation period and hence represent successive observations of the same stream. The actual interaction region of the CIR is defined by increases in the plasma density and magnetic field ahead of the high-speed stream. Note the comparable intensities of C and O and the large He-O intensity separation during most of the time period shown.

3. DISCUSSION

Nearly all of the features of the FIP effect for SEPs seen in Figure 2a have been discussed at length by Meyer (1985a). The enhancement in the low–FIP elements is a factor of ~ 4 for elements with FIP < 10 eV. The suppression of He by a factor ~ 2 was noted by Meyer (1985a) but not considered in detail. The recent model of von Steiger & Geiss (1989) describes the fractionation in terms of the differential diffusion of initially neutral ions out of a narrow magnetic filament as they are transported up toward the corona. Since the time required to ionize He is long compared with that for O or Ne, long transport time scales will allow neutral He to continue to leak from the filament after O and Ne are ionized. Thus, in this model, the relative depletion of He depends upon the speed of the fractionation process.

The FIP effect for the CIR abundances differs in three respects from that of the SEP abundances: (1) The magnitude of the low–FIP enhancement is reduced to a factor of ~ 2.5. (2) The ionization threshold between the low– and high–FIP groups has moved upward so that S and C now lie in the
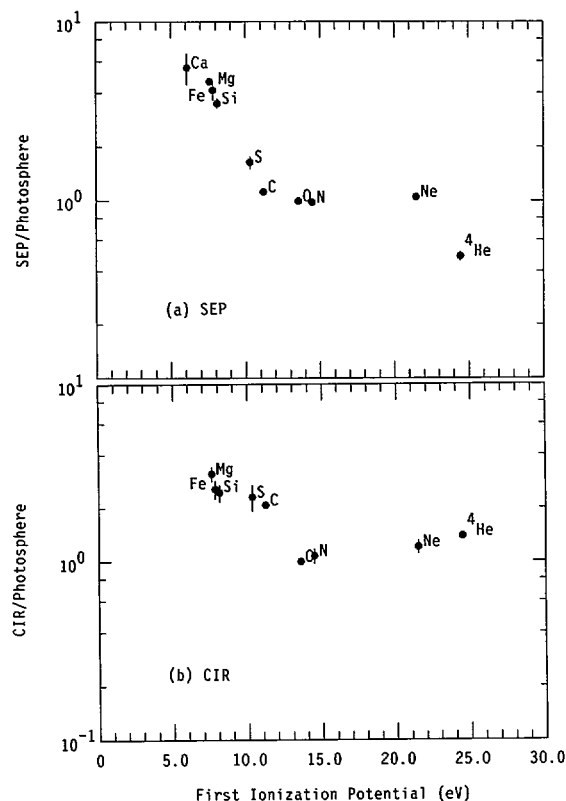
FIG. 2.—Abundances of elements from energetic ions in (a) large-flare solar energetic particle (SEP) events (from Cane, Reames, & von Rosenvinge 1991) and from (b) corotating interaction regions (CIRs) are normalized by the solar photospheric abundances (Anders & Grevesse 1989) and plotted as a function of FIP. The familiar FIP effect is seen for the SEP abundances. Those in CIRs show an altered FIP effect that arises from altered fractionation in the solar chromosphere beneath the coronal holes that give rise to the high-speed solar wind.

TABLE 1

ELEMENT ABUNDANCES RELATIVE TO OXYGEN (%) VERSUS FIRST
IONIZATION POTENTIAL

Element	FIP (eV)	Photosphere[a]	SEP[b]	CIR
^{4}He	24.46	11,430	5520 ± 300	15,900 ± 101
C	11.22	42	48 ± 2	89 ± 3.6
N	14.48	13.1	13 ± 1	14 ± 1.4
O	13.55	100	100 ± 2	100 ± 3.7
Ne	21.47	14.4	15 ± 1	17 ± 1.6
Mg..........	7.61	4.5	21 ± 1	14 ± 1.4
Si	8.12	4.2	15 ± 1	10 ± 1.2
S	10.30	2.2	3.5 ± 0.4	5 ± 0.8
Fe	7.83	3.9	16 ± 2	9.7 ± 1.1

[a] Anders & Grevesse 1989.
[b] Cane, Reames, & von Rosenvinge 1991.

high-speed streams; however, solar wind abundances measured inside the magnetosheath during high-speed solar wind streams (Gloeckler & Geiss 1989) are similar but not identical to those in Figure 2b. These direct solar wind measurements show a low–FIP enhancement of ∼2.5 and a displacement of the threshold that raises the abundance of S and slightly raises the abundances of C, but the abundance of He seems unaffected. It is, of course, possible that different high-speed streams arise from regions with different degrees of fractionation. Examination of the abundances in four of the largest CIR events, however, shows no evidence of a significant departure from the averages shown in Figure 2b. It is likely that the energetic particles that we observe accumulate over a long time period. As the particles propagate inward from the shock, they eventually mirror in the increasing magnetic field and return to the shock, thus remaining trapped in the high-speed stream for an extended period.

In summary, the abundance measurements clearly suggest that the chromospheric fractionation region beneath coronal holes differs from that region elsewhere on the Sun. Models of the region beneath high-speed solar wind streams should incorporate higher temperatures and shorter spatial and temporal scales. A reduced FIP effect lying between the photospheric and "coronal" abundances is not adequate to explain the abundances observed above coronal holes.

Finally, we note that these observations only increase the great similarity between abundances in the heliosphere and those in the Galactic cosmic-ray (GCR) sources. In his abstract, Meyer (1985b) states that "Only C is clearly more abundant in GCR sources than in SEP ... ." We have identified a heliospheric source that can produce the same enhancement of C/O that is observed in the GCR sources, and we can understand that enhancement in terms of a modest elevation of the temperature in the fractionation region. The greater suppression of high–FIP ions O, Ne and especially He, in GCR sources, might result from a longer fractionation time. Evidently, the stars that injected material that was accelerated to become the GCRs some 10^7 yr ago, were more similar to our Sun than we previously imagined.

low–FIP group. (3) He is not suppressed relative to O or Ne. The higher ionization threshold suggests a higher temperature in the fractionation region so that S and C are ionized. Reductions in the enhancement of low–FIP ions and in the suppression of He are both in qualitative agreement with the effects of a shorter fractionation time in the model of von Steiger & Geiss (1989).

Models which explain the enhancement of the low–FIP elements in terms of the coronal accretion of metal-rich cometary or asteroidal dust (Grün et al. 1985) would seem to be ruled out by the observed abundance variations. It seem unlikely that different elements (especially S, C, and He) would accrete in different regions of the corona.

Since the energetic particle abundances in the CIR–related events were measured inside the high-speed solar wind streams, it is likely that they directly represent the abundances of the high-speed wind. CIR shocks usually form outside 1 AU, and particles accelerated by the forward shock in the low-speed wind are rarely seen at 1 AU, while those accelerated by the reverse shock from the high-speed stream move more directly inward toward Earth. In contrast, SEP abundances presumably reflect abundances in the corona and low-speed wind near active regions where coronal mass ejections drive large shocks.

Direct solar wind abundance measurements are difficult in

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